Free Electron Laser Technology Status in the United States

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The purpose of this paper is to provide an overview of the Free Electron Laser weapons development program from its beginnings in 1979 to the present. A historical overview of the programmatics will be provided but the primary emphasis will be the technical accomplishments made during this period.

1. Introduction

Because of its potential, the Department of Defense (DoD) became very interested in the Free Electron Laser (FEL) after John Madey first demonstrated a 3.4 μm FEL oscillator at Stanford in 1977. The FEL promised high power with excellent beam quality and selectable wavelengths. During the early years, the funding was limited but much of the theory of FEL operation was verified. DoD components actively involved in FEL research during this period were the Air Force Office of Scientific Research (AFOSR), the Army Space and Strategic Defense Command (USASSDC) then known as the Ballistic Missile Defense Command, the Defense Advanced Re-search Projects Agency (DARPA, now ARPA) and the Office of Naval Research (ONR). The success of these early efforts prompted the Strategic Defense Intitiative Organization (SDIO) in early 1985 to start development of a ground based laser (GBL) system for defense against ballistic missiles. The GBL was to be powered by either an induction FEL, a radio frequency FEL, or an excimer laser. The estimated cost for fiscal years 1985 through 1989 to demonstrate a GBL system was $1.7B [1]. Actual funding during the 7 years 1985 through 1991 was $905M [2]. The funding for the laser portion of this effort was $654M ($159M on excimer lasers [1], $262M on the induction FEL, and $232M on the RF FEL). The rest of the funding was spent on beam control and atmospheric compensation ($125M), relay mirrors ($15M), facility construction ($77M), and system integration ($35M). All of these numbers come from USASSDC financial records [2] except for the excimer laser funding numbers [1].

In 1989, the excimer laser was eliminated as a candidate because of technical difficulties encountered during tests at White Sands, its low electrical efficiency, and the difficulty in propagating its short wavelength (<0.4 μm) through the atmosphere.

In 1990, after a formal 2 year competition between teams composed of TRW/Lawrence Livermore and Boeing/Los Alamos, the induction FEL was eliminated. A contract was awarded to the Boeing/Los Alamos team to build a multi-megawatt RF-FEL at the Orogrande site at White Sands Missile Range. In December 1990, the GBL program was terminated, and most of the funding provided by SDIO for the remainder of FY91 was spent in program termination.

By the end of FY91, a much less ambitious program, named the Average Power Laser Experiment (APLE), had been restructured out of the GBL program [3]. This program was to build a 100 kW (400 kW peak) power laser at 10 micron and use much of the hardware developed for the GBL program such as the RF power and wiggler. However, funding during the next several years did not meet the FY91 SDIO schedule guidance. This shortfall caused the stretched out APLE program to grow in cost from $85M to $97M and grow from 3+ years to 6+ years in duration. In December 1992, SDIO transferred the FEL program to the Secretary of the Army for Research, Development, and Acquisition (SARDA) including FY93 and FY94 funding and outyear funding authorization. In March of 1993, SARDA redirected the funds which forced USASSDC to terminate the program in June of 1993 due to lack of FY94 funding. Congress was notified and $5M was added in May of 1994 to a Navy line item (because SARDA redirected the SDIO funding and did not want to continue the program) specifically to continue the FEL program at Boeing using the USASSDC contract. The program was restarted in June 1994 resulting in an entire year of no activity except those associated with termination and hardware disposition. The congressional plus-up will continue the program through FY95. Additional funding past that date is uncertain. This program history is summarized in Figure 1.

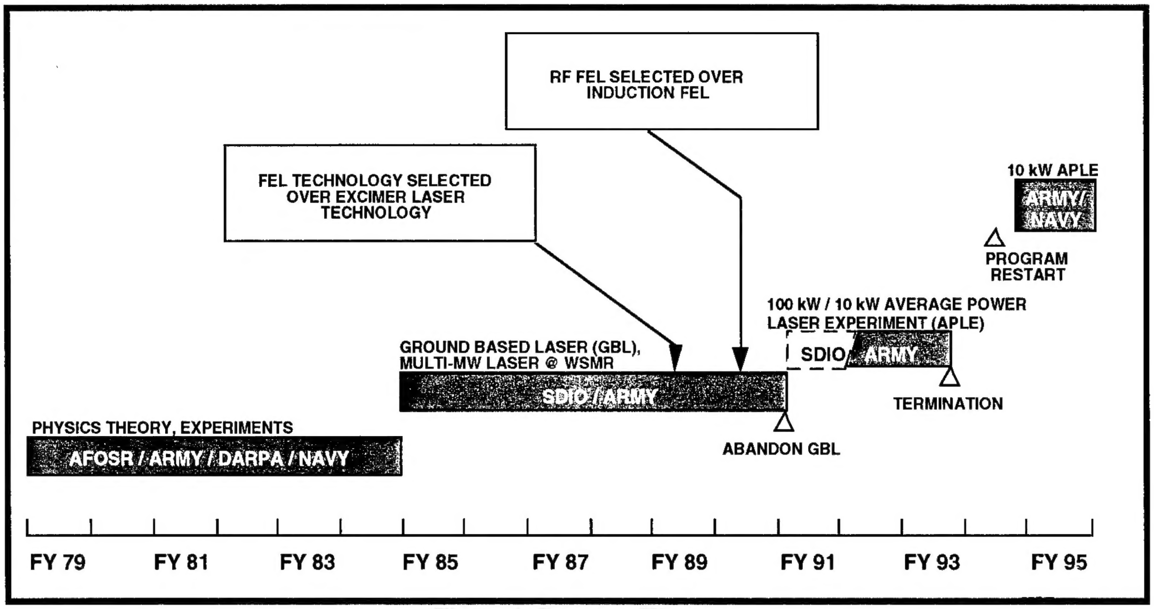

Figure 1. Program History

2. Fundamental FEL Weapon Requirements

To produce a hard target kill, a laser weapon system must have enough average power to produce burn through. Power requirements vary with the deployment scenario of the laser weapon and the missile system to defend against. Typically, ground tactical deployments for missile kill at ranges less than 10 km require average powers of 100's of kWs and airborne deployment for ranges up to 500 km require a few MWs. The requirements for the ground based laser were even greater. To achieve a reasonable beam divergence and spot size on the target, the laser beam must have good beam quality and operate at short wavelengths (<4 μm) since the spot size on target is directly proportional to the beam quality and the wavelength. This requirement becomes more severe as the range increases. Wavelength selectability is required to allow laser operation at wavelengths in which propagation windows exist. These windows exist at 0.8μm, 1μm, 1.3μm, 1.7μm, 2.2μm, and 3.8μm. While tunability during operation is not required for most applications, it would be desirable in a laser countermeasures application. In addition, high efficiency is also required to reduce power requirements and weight.

3. FEL Development Approach

In the initial days of FEL development, many of the unknowns about basic FEL operation could be answered at low power without the added complications and cost associated with high average power operation. Some of these unknowns were laser start up, electron beam stability, and control of emittance growth. Low power testing allowed for demonstration of all the key weapon requirements, i.e. power (burst mode), beam quality, short wavelength, tunability, and efficiency, and was considered a valid develop-ment approach because the electron bunch structure during the burst, called a macropulse, would be exactly the same as in the actual weapon. Also, the macropulse would be long enough such that enough electron bunches would be passed through the system to achieve steady state operation. This is explained further in the next paragraph. Once the basic operation of the FEL was demonstrated, the duty cycle could be increased to achieve high average power by designing the system to allow for removal of heat from the accelerator.

A CW (100% macropulse duty factor) FEL produces high power pulses of light. These pulses are called micropulses which typically exceed 100 MW. A typical CW system would have micropulses 20 ps long separated by 20 ns (an integer factor times the inverse of the RF frequency). This gives a micropulse duty factor of 0.1%. In a pulsed system (macropulse duty factor is less than 100%) the micropulses are the same as the CW case. However, the RF power is turned off before the system has a chance to overheat and allowed to stay off for a short period of time before being turned back on. These packets of micropulses are called macropulses. A typical pulsed system would have macropulses of

10 μs duration which would contain 500 micropulses for the micropulse repetition rate of 50 MHz (1/20 ns) used above. The macropulses would typically be separated by 100 ms. For a micropulse power of 100 MW, this would give a macropulse average power of 100 kW but a true average power of only 10 W. The macropulse duty factor in this case would be 0.01%. The macropulse power is what the weapon system would produce if the macropulse duty factor was increased to 100%. The macropulse power could be increased to greater than 100 kW by either increasing the micropulse power and/or by increasing the micropulse repetition rate.

4. FEL Weapon Development Issues Resolved

Shown in Figure 2 are some of the more significant demonstrations performed during the period between 1982 and 1992. Shown are the Los Alamos experiments which demonstrated wavelength tunability from 9 to 35 μm. These experiments demonstrated that not only could the FEL operate at different wavelengths but that the FEL could operate at different wavelengths with the same machine. Also shown are the Boeing experiments which demonstrated operation at very short wavelength (0.5 μm and 0.6 μm) while producing the high micropulse power and good beam quality required for a weapon. This demonstration was particularly significant since FEL operation becomes increasingly more difficult as the wavelength is reduced. Beam qualities of less than 1.05 times the diffraction limit were demonstrated on this experiment and others and have shown that FELs inherently produce good beam quality. Also shown is the photo-injector experiment at Boeing that demonstrated weapon level injector performance (current, charge density, and emittance) by achieving 175 kW. This demonstrated the world's highest average power electron beam for a photoinjector accelerator (by more than 600x). This photo-injector would be the front end for the APLE demonstration. These experiments (and others) will be discussed in more detail in the following sections.

By the end of 1992 all of the key weapon requirements including power (burst mode) beam quality, operation at short wavelength, turnability, and efficiency had been demonstrated and the only remaining FEL issue was the demonstration of high average power. This was the objective of the Boeing/Los Alamos Average Power Laser Experiment (APLE) mentioned above and discussed in detail in Section 6.

5. Major FEL Accomplishments

The major FEL accomplishments in the last fifteen years are:

- High peak power demonstrated
- Extremely good beam quality demonstrated at short wavelengths
- Wavelength agility demonstrated
- High efficiency wiggler technology developed
- Energy recovery proof of principle
- High power optics demonstrated
- FEL design and analysis codes developed
- High brightness photoinjector technology developed and demonstrated
- Weapons designs completed

High peak power is required because this leads to high average power as the duty factor of the macropulse is increased. Wavelength agility is important to allow the wavelength to be selected based on propagation and lethality requirements. High efficiency wigglers and energy recovery are desirable to reduce the prime power, RF power, and the cooling system requirements. Good beam quality at short wavelength is important to achieve low beam divergence and small spot sizes on the target. High power optics are required for weapons operation. Extensive FEL analysis and design codes were developed and verified giving a high confidence in proposed weapon system design and the weapons demonstrator program (APLE). The high brightness photoinjector technology necessary for a weapon has been developed and demonstrated. The weapon system design for the ground based laser reached PDR; conceptual designs for the airborne free electron laser, and the short range tactical high energy laser were also completed. As can be seen from this list, many significant accomplishments have occurred in the U.S. weapons development program.

5.1 High Peak Power Demonstrated

The Boeing experiments known as High Average Power (HAP) [4a,b,c] generated an intracavity peak power of 250 MW at 0.5 μm and 0.6 μm wavelength with a concentric FEL resonator cavity (see Figure 3). This peak power was generated for a 10 picosecond pulse at a 4 MHz pulse repetition rate. The 200 μsec macropulse average power was 2 kW and the overall average generated power for a 5 Hz macropulse rate was 2 W.

In another experiment in the HAP series, the FEL oscillator configuration was a ring resonator consisting of hyperboloid grazing

mirrors and parabolic collimating mirrors which recycled light back through the oscillator wiggler. The resonator optics were uncooled prototypes of the Ground Based Laser design. The injector was a thermionic injector which produced

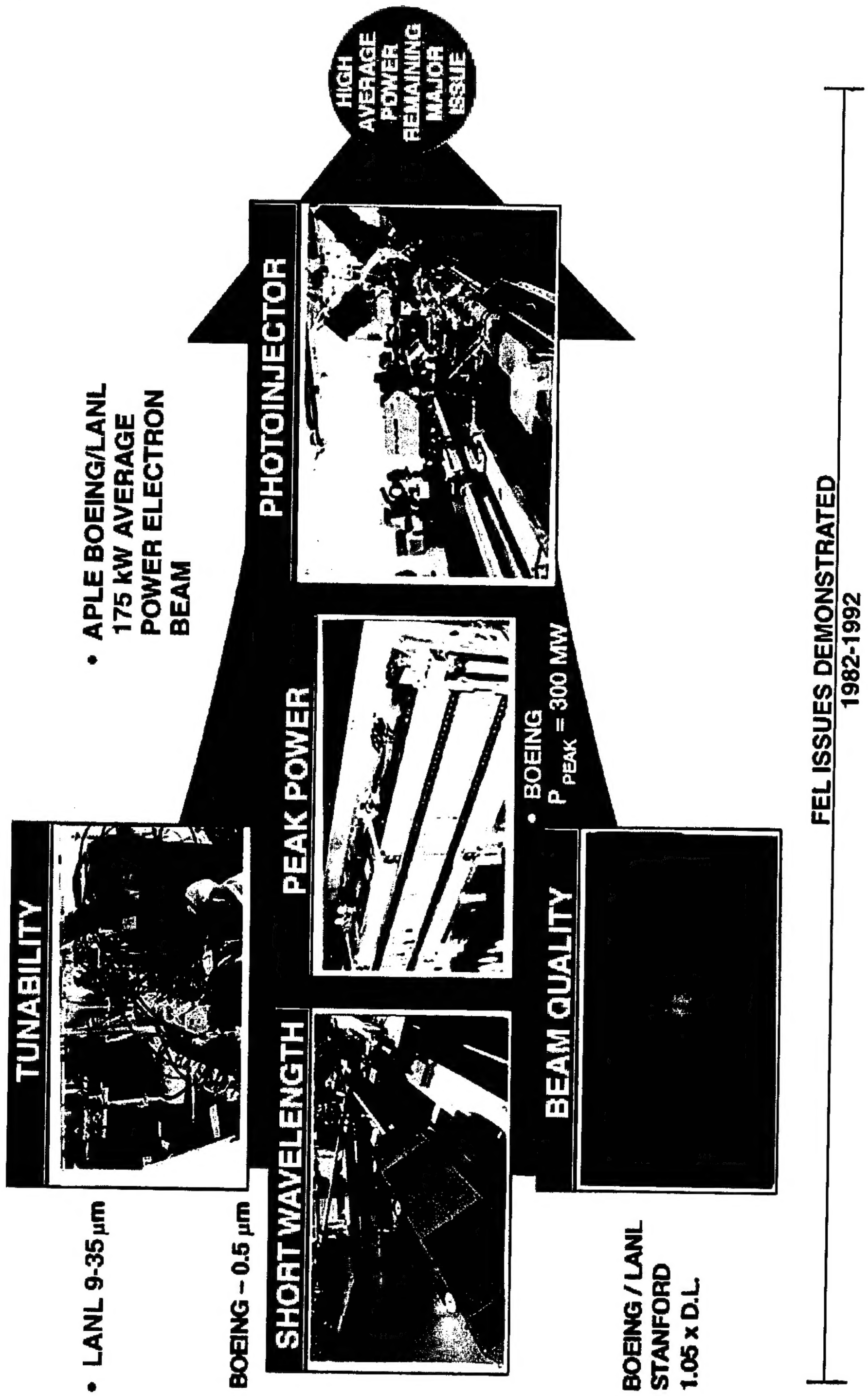

Figure 2. Major FEL Accomplishments

a micropulse current of 300 A and an average current of 18 mA during the macropulse. The demonstration used a 120 MeV accelerator powered at 1300 MHz. A 5 meter untapered wiggler built by Spectra Technologies, Inc. (STI) was used as the central portion of the oscillator and achieved a 0.1% extraction efficiency. This extraction efficiency could have been increased to 3-6% by using a photoinjector with higher peak current and lower emittance.

This demonstration was the first step on the path to generating a high average power short wavelength FEL. Since the validity of short wavelength operation is independent of duty factor, the high peak power HAP experiment avoided major investments in CW RF power. The experiment did successfully demonstrate the feasibility of achieving high average power outputs at short wavelength with scalable FEL technologies with the exception of high average current injectors. However, since the HAP experiments, a high average current injector has been developed and demonstrated in the APLE program and will be described in a Section 6.

5.2 1.05 Beam Quality Demonstrated

Another FEL advantage is near diffraction limit beam quality. Since the brightness of the device is reduced by the square of the beam quality factor, small variations in beam quality significantly influence the ultimate capability of the laser to deliver lethal energy at useful ranges. FELs inherently produce high quality beams which can be focused down to spots near diffraction limit unlike other laser candidates such as chemical lasers.

The HAP experiments demonstrated this attribute by producing strehl ratios around 0.9 (strehl is roughly the ratio of the peak intensity at the center of the focus to the value expected from a diffraction-limited beam) for a 6 MW output laser beam at 0.6 micron wavelength [4]. This strehl corresponds to a beam quality of 1.05 times the diffraction limit.

Experimental data from Los Alamos [5, pg. 316] shows results from a 10.4 micron wavelength experiment where the strehl was measured at 0.92. This results in a beam quality of approximately 1.04.

High beam quality (high strehl) in free electron lasers results from the fact that the Fresnel number for FELs is typically small. The Fresnel number, an important measure of diffraction, is proportional to a/w where a is the resonator mirror size and w is the beam waist at the mirror. A small Fresnel number means that the fundamental mode of the laser will fill the mirror and higher order modes will 'spill-off' the mirror. This spatial filtering results in high losses for all but the fundamental mode which contributes to the beam quality.

5.3 Wavelength Agility Demonstrated

One feature of the FEL is the ability to tune the device over a broad wavelength regime with the same hardware. Several contributors to FEL technology have demonstrated this capability during the course of their investigations. For example the wavelength agility demonstrated at Vanderbilt, Stanford, Duke, LANL, and Boeing/STI are shown in Figure 4 [5,6].

The ability to tune the FEL wavelength is illustrated in the equation below (in SI units) that describes the wavelength of a free electron laser (λ_L).

$$\lambda_L = \lambda_w \left(1 + A_W^2 \right) / \left(2 \gamma^2 \right)$$

where

$$A_W = \lambda_w e B_o / (2 \pi m_o c)$$

(the wiggler parameter)

and

$$\gamma = 1 + E_k / (m_o c^2).$$

(the relativistic parameter)

Inspection of the above equations shows that the wavelength can be tuned by: (1) adjusting the e-beam kinetic energy (E_k), (2) adjusting the wiggler period (λ_w) and/or (3) changing the strength of the wiggler magnetic field (B_o).

The wavelength is directly proportional to the square of the energy so halving the e-beam energy (which is a typical capability of some accelerators) increases the wavelength by a factor of four. Adjustments to the wiggler period are determined by the construction of the wiggler. To accomplish tuning using this approach, the steer/focus properties of each wiggler section versus gap size must be measured and incorporated into the computer controls. Both the wiggler period and the strength of the magnetic field can be adjusted in this manner. Additional tuning of the wavelength can be accomplished by using grating rhombs for line selection. Tilting the gratings to tune the wavelength of the FEL was the approach taken by Boeing for their burst mode experiments. The Boeing grating rhomb was designed for 5 percent tunability with an efficiency loss of less than 1 percent.

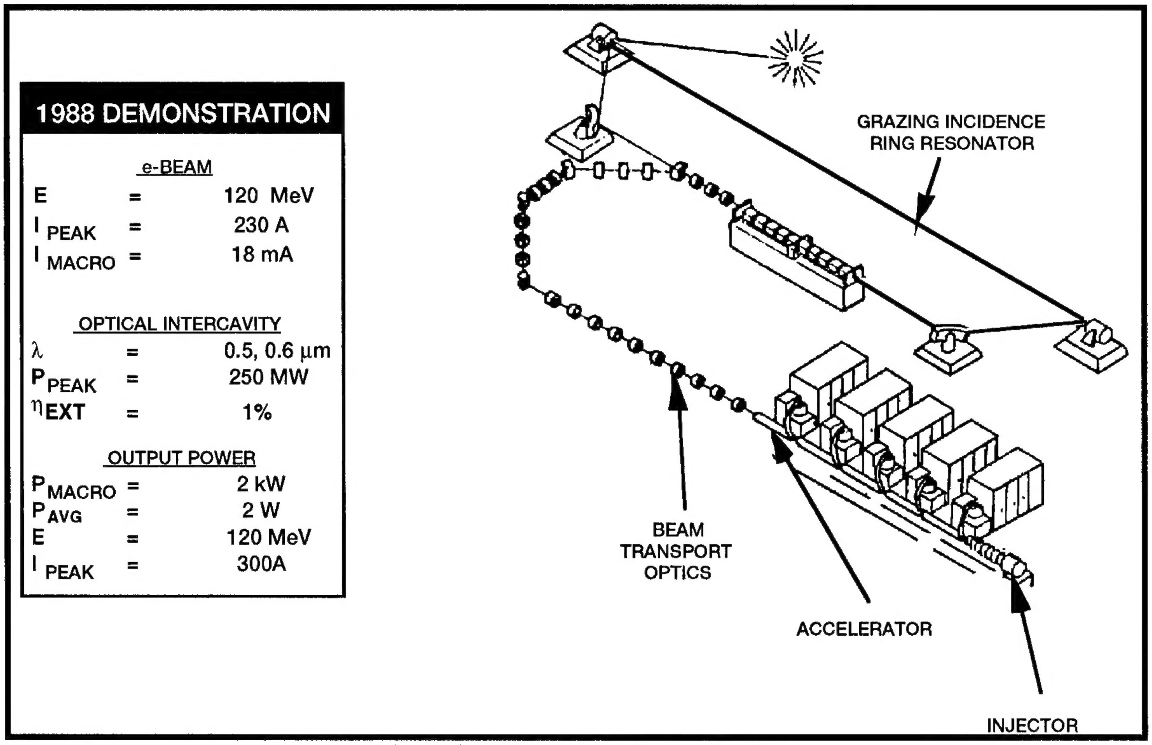

Figure 3. High Average Power Facility

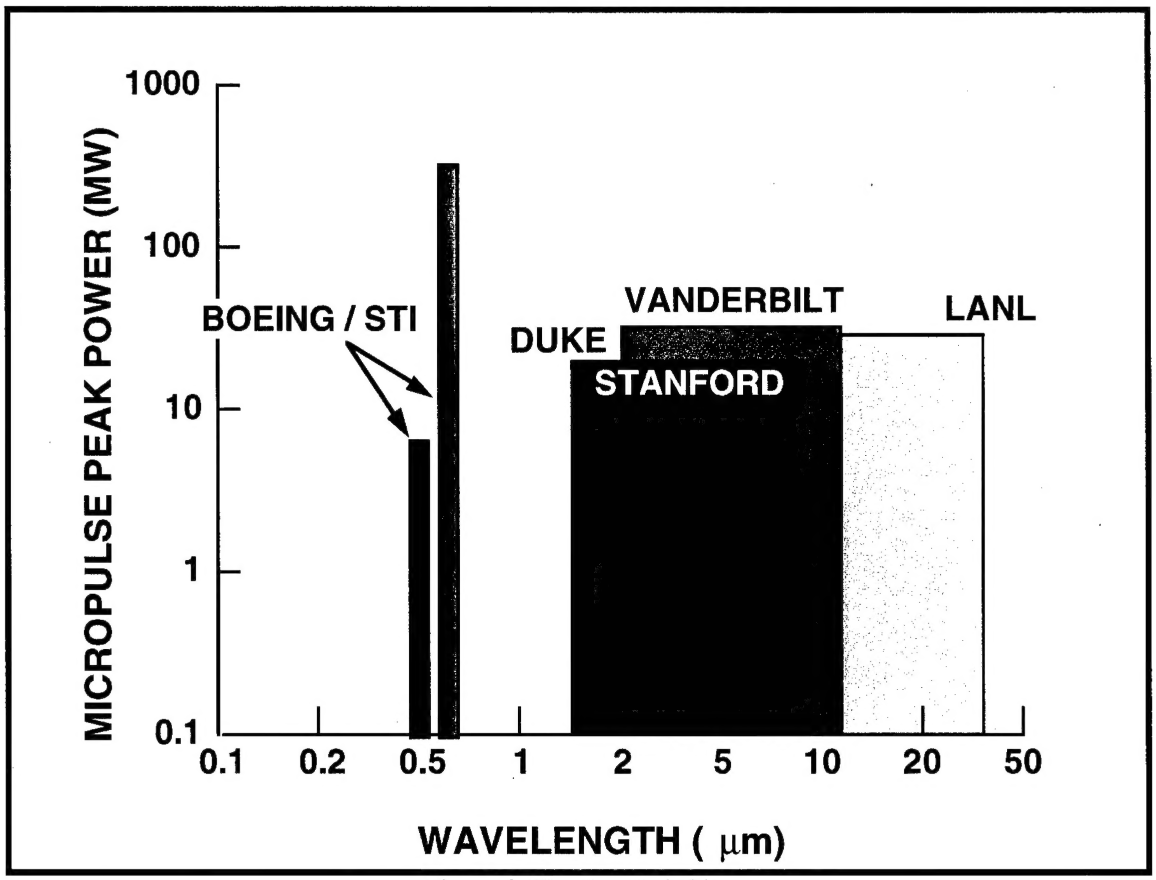

Figure 4. Wavelength Agility

5.4 Progress in Wiggler Technology

Dr. John Madey derived the free electron laser from quantum mechanical principles and proved it's existence with the first FEL amplifier in 1976 and subsequently the first FEL oscillator in 1977 (at 3.2 to 3.4 micron wavelength) [5]. The Mark III FEL was built by Dr. Madey while at Stanford University, and similar designs have been used at Duke University and Vanderbilt University to produce extraction efficiencies of 0.2 to 0.6% at IR wavelengths from 1.4 to 10 microns [12].

Because there were no electron beam sources with enough electron current and satisfactory beam quality in the 70's, it was not until 1982 that the second FELs were operated in the optical part of the spectrum. The Los Alamos National Laboratory and the Boeing/Mathematical Science Northwest FEL were very similar and configured as amplifiers. LANL used a 1 meter linearly tapered wiggler and obtained 3.7% extraction efficiency while Boeing/MSNW used a 2.3 meter tapered wiggler for a 4.4% extraction efficiency (both FELs operated at 10 micron). By using a 30% taper and a prebuncher LANL has obtained a 4.4% extraction efficiency oscillator at 10 microns with a 1 meter wiggler. In 1986-87, Boeing used their 110 MeV RF linac and a concentric resonator to get 1% extraction at 0.5 and 0.6 microns. They reconfigured the concentric resonator to a ring resonator in 1990. The Boeing/Spectra Technology Inc. FEL holds the record for shortest wavelength (0.5 micron) in the USA but Russia holds the world record of 0.24 micron.

The highest measured FEL extraction per unit of wiggler length efficiency was 35% from the LLNL Induction Accelerator Electron Laser Facility using microwave wavelengths and operating at 6860 microns. Since this device did not address some optical wavelength issues LLNL built another induction FEL amplifier which had the longest wiggler ever built, i.e 25 meters. This wiggler produced 1.4% extraction efficiency at 10.6 microns. Even though the peak current produced by the induction linac was considerably higher than that produced by rf linacs, the large increase in wiggler extraction efficiency expected (proportional to the peak current) was not obtained due to the large emittance of the induction linac e-beam.

The Near-Infrared Scaleable Undulation System (NISUS) wiggler which was to be used with APLE is discussed in that section.

The Accelerator Wiggler was an advanced concept to produce high extraction efficiencies. The idea was to incorporate e-beam accelerators as an integral part of the wiggler so that energy extracted from the e-beam by the wig-gler subsections could be immediately restored. A design was completed and most of the hardware built at Stanford University before funding was terminated.

The major wiggler technology milestones are summarized in Figure 5.

5.5 Energy Recovery Experiments

The ability to recover energy from an electron beam after energy extraction by a wiggler will most likely be required when considering high power lightweight/compact designs. In addition to reducing power requirements, energy recovery allows a means for slowing the e-beam down; a desirable result when the spent e-beam must be dumped or stopped. The ability to efficiently recover the energy used in accelerating the beam not only reduces the power requirements but also reduces the amount of radiation generated in dumping the residual electron beam.

With a potential of 90 percent energy recovery, significant decrease in platform mass can result and a wall-plug efficiency as high as 25% may be attainable. This can be expressed as:

$$\eta_{total} = \frac{\eta_{power}\,\eta_{accel}\,\eta_{FEL}}{1 - \eta_{accel}\,\eta_{er}\,(1-\eta_{FEL})}$$

where

η_{power} = power conversion efficiency (70% is possible)

η_{accel} = efficiency of converting RF power to e-beam power (typically 85%)

η_{FEL} = efficiency of extracting the optical power from the e-beam (typically 15%)

η_{er} = efficiency of energy recovery

Two primary concepts have been considered for accomplishing energy recovery. The first is using a dual linac with a deaccelerator section to couple RF energy back into the accelerator section across a bridge section of waveguide. The other concept is called single-cell recovery where electrons are sent through the same accelerator except 180 degrees out of phase with the accelerated beam. The latter concept has significant advantages in compactness but may be difficult to implement due to the large longitudinal beam spread caused

by energy extraction in the wiggler.

In 1986-87, Los Alamos configured a dual linac beam line (accelerator/decelerator) with two bridge couplers connecting twin 10 MeV accelerator sections to their deaccelerator counter-parts [9]. The electron microbunches were first accelerated to 20 MeV by a series of $\pi/2$ mode side coupled cavities operating at 1300 MHZ and driven by two Thompson-CSF 5.5 MW klystrons. After passing through the 1 meter (0.7% extraction efficiency) wiggler the electron beam had more than 95% of its original energy with an energy spread of 8 to 10% (introduced by the lasing action). Each decelerator is electrically the mirror image of its corresponding accelerator and for this resonant bridge-coupler design the maximum deceleration measured was 75%. The test configuration is shown in Figure 6.

5.6 Hyperboloid Grazing Mirror

For high energy laser applications, the beam at the wiggler exit can be very small (pencil diameter or less). This beam is stressing to optics at normal incidences producing fluxes of MWs / cm^2. Los Alamos conducted tests for silver coated mirrors in the late 80's which confirmed that the primary effect on these mirrors from an FEL beam is thermal. Tests were conducted with a 100 microsecond train of 10 ns pulses at 100 MHz. Tests were also conducted with a 3 ms train, and the decrease in threshold followed the theoretical prediction. In addition, the effect of incidence angle on damage threshold was confirmed. Los Alamos simulated an RF FEL pulse structure by using a solid state laser FEL simulator at 1.06 microns wavelength. The damage thresholds were measured as a function of incidence angle. At incidence angles greater than about 65 degrees, measurements were made at KMS Fusion where their laser could achieve energy densities required to observe damage.

Grazing optics as demonstrated by these tests can substantially reduce the flux on the mirror by taking advantage of the increased reflectance of the coatings at grazing incidences and by the spreading effect of the beam at these angles. As shown in Figure 7, the $1/\cos^2$ curve fit agrees with the observed data fairly well.

Figure 8 shows a 64 cm long grazing hyperboloid mirror. This mirror was produced by cutting a pie section from a polished silicon bullet. The mirror exhibits low-spatial frequency wavefront error of $\lambda/14$ peak to peak and high/mid spatial frequency wavefront error of $\lambda/38$ rms. Subsequent to the initial fabrication effort, a 62 cm long silicon heat exchanger was fabricated and integrated with the face plate. Bonding and leak checks were successfully completed on this unit.

5.7 FEL Design and Analysis Codes

LANL developed an FEL design and analysis code called INEX (Integrated Numerical Experiment) that modeled electron transport from the cathode surface to the final electron dump. The injector and accelerator sections used a code called Phase and Radial Motion in Electron Linear Accelerators (PARMELA) which integrated several accelerator codes used by other National Laboratories and accelerator facilities for analysis of electron beams. The Wiggler and Optics sections used Free Electron Laser Integrated Experiment (FELIX) which evolved from other FEL and resonator codes. The beam transport to the electron dump again used PARMELA.

INEX was bench marked against the LANL APLE Prototype Experiment (APEX) FEL and proved to be very accurate [7]. An example of this is shown in Figure 9. The individual codes that make up INEX have also been verified on many other experiments conducted by many National Laboratories and Contractors.

5.8 Injector Technology

A breakthrough in e-beam sources was realized with the development of the photo-injector which through photoemission provides very high brightness electrons to the accelerator. The electron bunch length and repetition rate of the FEL micropulse is continuously variable by changing the pulse format of the photoinjector drive laser. A schematic of a photoinjector is shown in Figure 10.

Issues associated with these photo-injectors were photochathode lifetime, quantum efficiencies, and emittance. The Boeing/Los Alamos team has demonstrated the technology in the APLE program, by building photoinjectors which have operating lifetimes of greater than an hour with a maintained quantum efficiency of 3% and greater. Measured normalized emittances have been less than 20 mm-mr. Typical materials used for photocathodes are LaB_6 (lanthanum hexaboride) and CsK_2Sb (cesium potassian antimony). Duke University has produced the highest brightness e-beam to date (10^{12} A/m^2rad^2, emittance down to 10 mm-mr) with continuous run times, but the quantum

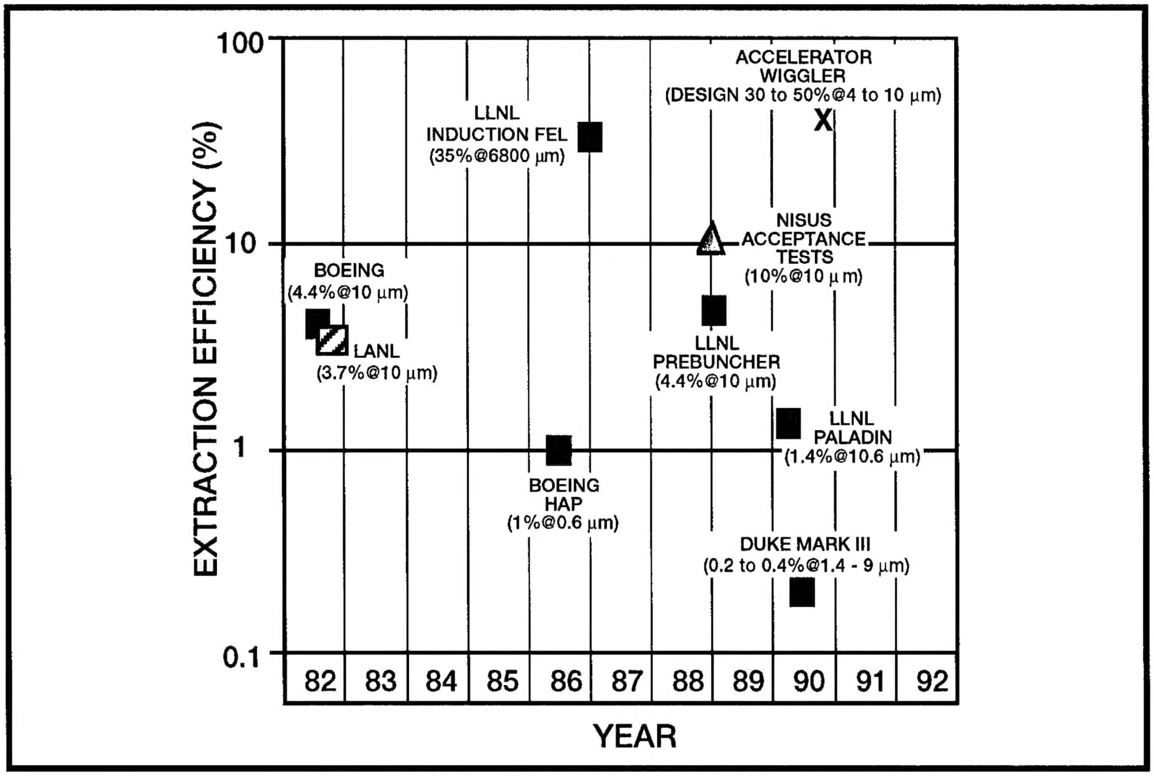

Figure 5. Major Wiggler Technology Milestones

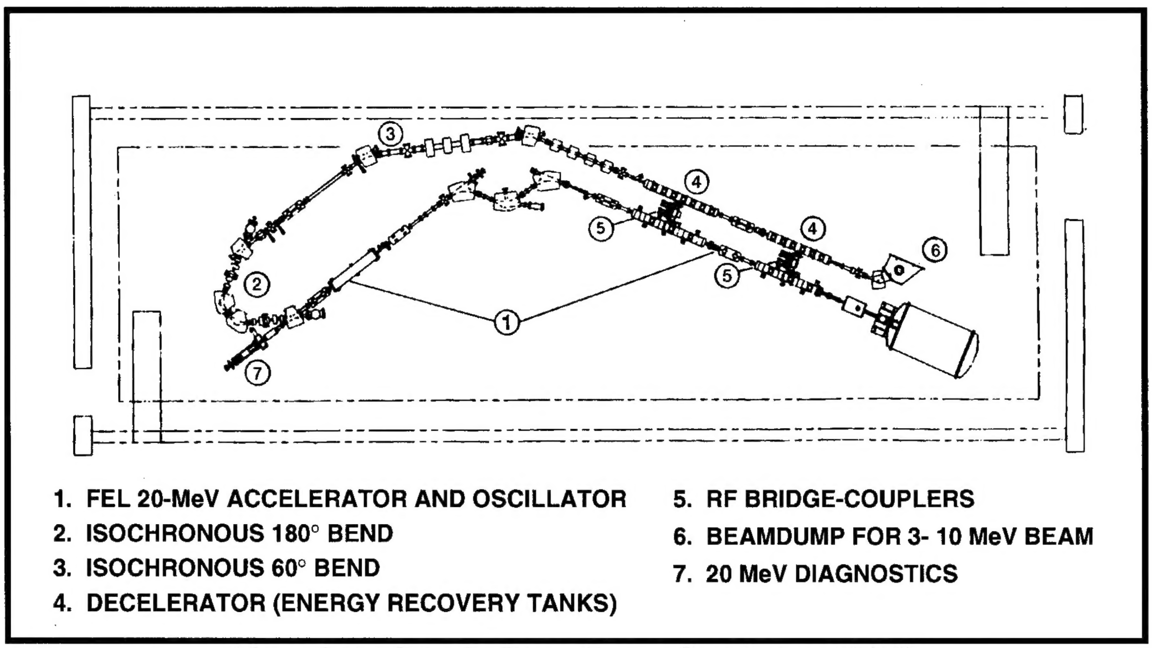

Figure 6. Test Setup for Energy Recover Experiments at LANL

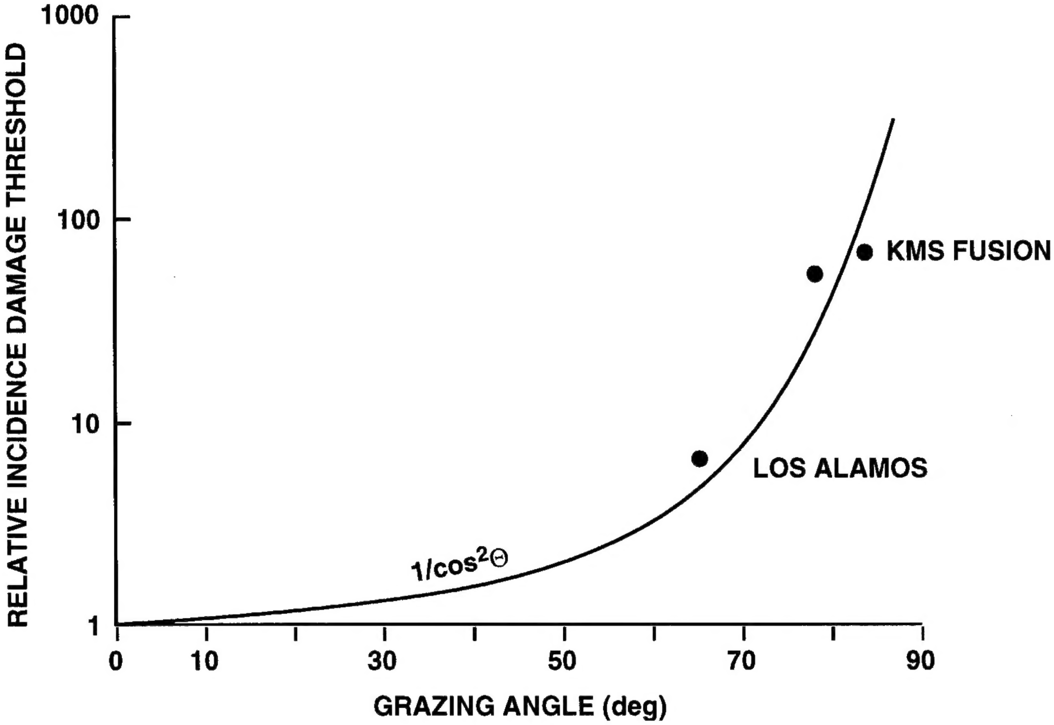

Figure 7. Mirror Coating Test Results

Figure 8. Hyperboloid Grazing Mirror

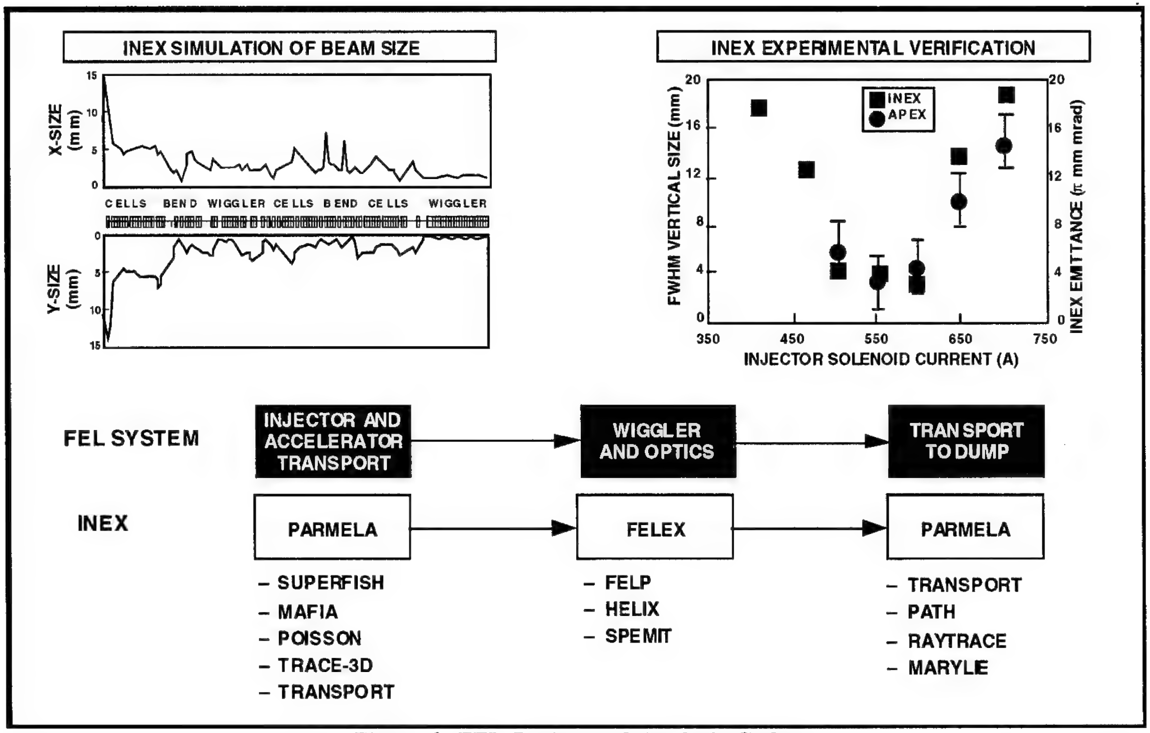

Figure 9. FEL Design and Analysis Codes

efficiencies are typically lower than the CsK_2Sb photocathodes.

5.9 High Duty Factor Electron Beam Achieved

In August and September of 1992 the APLE experiment team (Boeing/LANL) achieved 25 percent duty factor which was the APLE performance requirement. These tests demonstrated the production of 7 nC charge at the photocathode and acceleration up to 5 MeV energy. The 5 MeV beam had normalized emittance to 40 mm-mrad which was a factor of 2 better than the APLE requirement. This accomplishment is significant in that it is the first time that a photoinjector linac has produced high beam current (0.13 A average) at high duty factor (25 percent). An average power of 170 kW (675 kw peak) was achieved. [11]

Multiple runs of up to 5 minutes were performed at full power over a 30 minute interval to show that the beam could be turned on and off. The test hardware is shown in Figure 11.

6. Average Power Laser Experiment

6.1 APLE Status/Plans

The Average Power Laser Experiment (APLE) was a joint effort between Boeing's Space and Defense Division and Los Alamos National Laboratory to design and test a high average power free electron laser. The APLE laser was designed to produce a 400 kW peak, 25% duty cycle optical beam, lasing at 10.6 um wavelength, using a single accelerator master oscillator power amplifier (SAMOPA) configuration (see Figure 12). The machine was thermally designed to operate at 100% duty factor for a minimum of 3 minutes and would produce 400 kW average power with the addition of more rf power. The APLE program incorporates most of the existing hardware from the High Average Power (HAP) and Modular Components Technology Development (MCTD) programs [10], both originally part of the Ground Based Laser program until its cancellation in FY 91. The hardware is located at the Boeing Physical Sciences Center in Seattle, Washington. After demonstration of the laser, additional hardware could be added to the device to increase the power to weapons level requirements to support a variety of missions and basing modes (ground, mobile ground, airplane, space). Figure 12 shows the planned layout with associated existing hardware.

The original 1991 APLE program was modified in 1992 to provide an early Phase I demonstration of a 10 kW, 10 micron oscillator which would be sufficient to drive a 10 MW weapon system. During Phase II the amplifier stage would be added to the oscillator.

The injector qualification tests were successfully completed in 1992. This world-class

photo-injector development effort and the associated landmark tests will be discussed in detail below. The electron accelerator cavities for the 10 kW oscillator demonstration had been fabricated and were being assembled and the engineering design for the 100 kW SAMOPA was nearly completed prior to program termination in June 1993. The entire system had also been extensively modeled by Boeing and Los Alamos utilizing a number of modeling codes. Work resumed on assembly of the hardware for the APLE accelerator when the program was restarted in June 1994.

6.2 APLE Photoinjector

6.2.1 Description

The APLE injector design, has as a key component, the Los Alamos developed photocathode / drive laser subsystems. The photocathode chamber was developed so that a new photocathode can be positioned into place for use by the FEL without having to break vacuum. The drive laser is a solid state laser (1.06 microns) which is then doubled by a LBO crystal to the visible for illumination of the cathode. The power required for illumination is approximately 3 W average power. Micro-pulse energy is 0.47 μJ (@ 35 ps FWHM) with a repetition rate of 27 MHz. The macropulse format is 30 Hz with an 8.3 ms macropulse (25 % duty). The spatial profile of the laser beam is a 4.5 mm Gaussian.

The APLE injector RF cavities are made up of two cells the first of which practically envelopes the photocathode. Electrons exit this structure at about 2 MeV. In addition, an injector steering coil is located near the photocathode. Figure 13 shows the photocathode vacuum container in the foreground and the 5 MeV accelerator. The 2 large 433 MHz waveguides can be seen connected to the 5 Mev accelerator. This photocathode was demonstrated in the APLE injector at high average currents in 1992.

Key issues and performance characteristics of the photocathode are described below and are shown graphically in Figure 14.

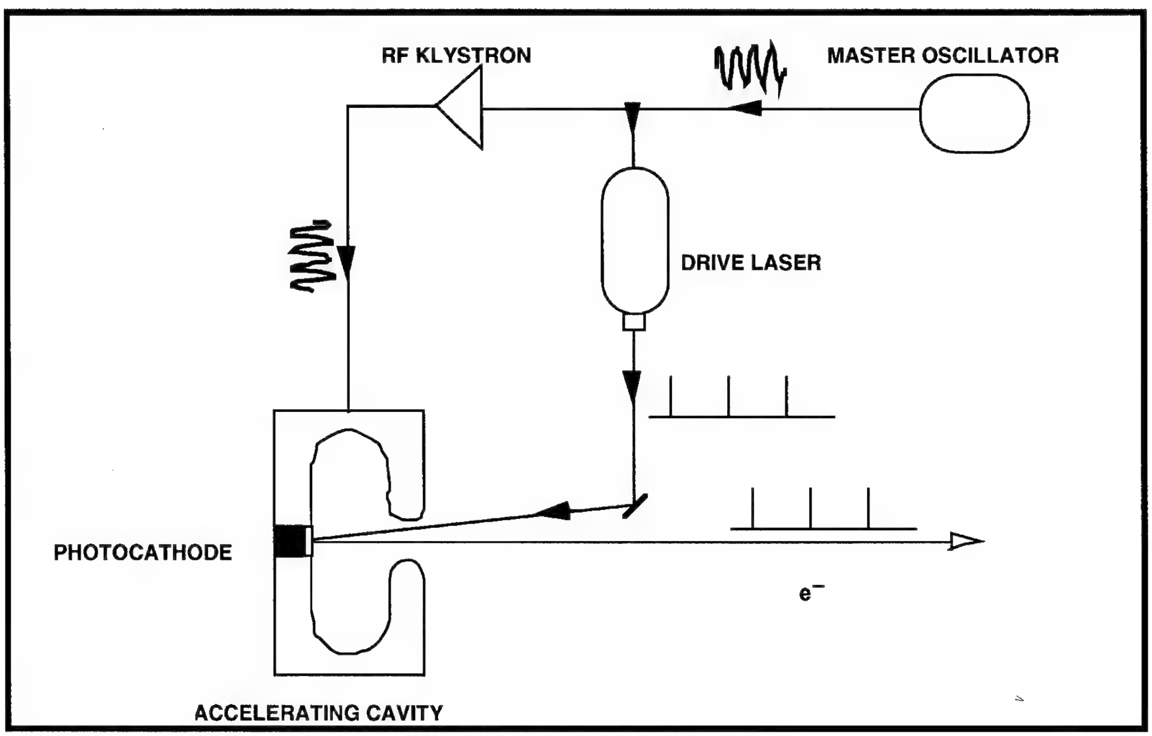

Figure 10. Photoinjector Schematic

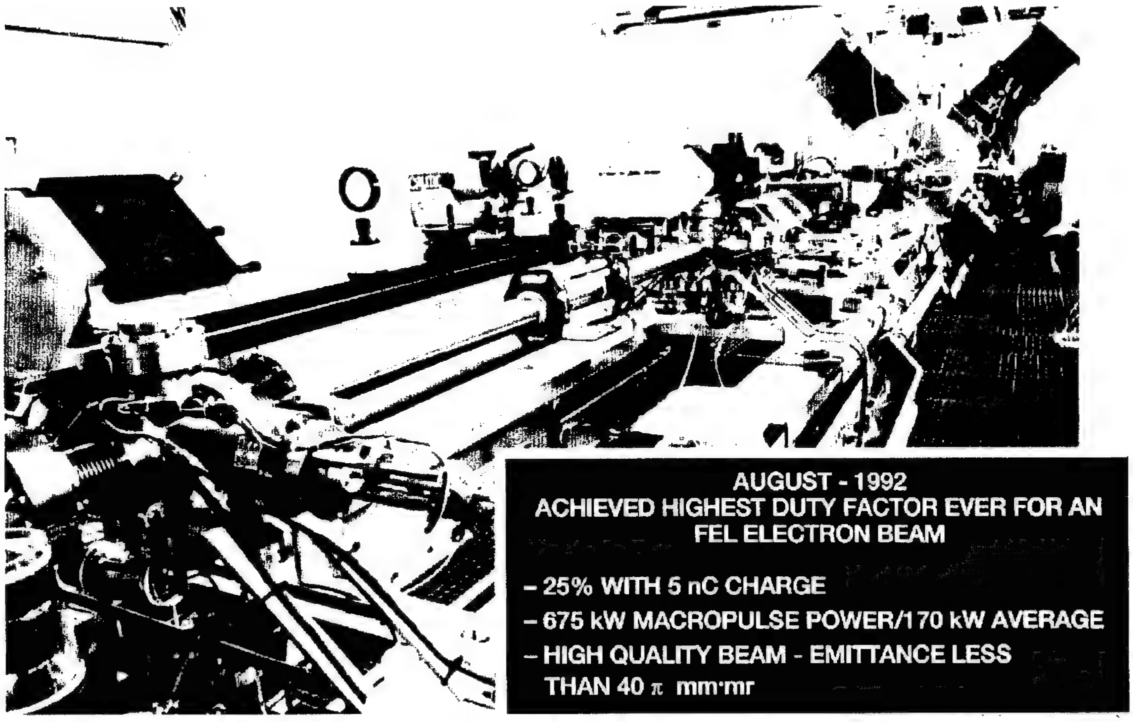

Figure 11. High Duty Test Setup

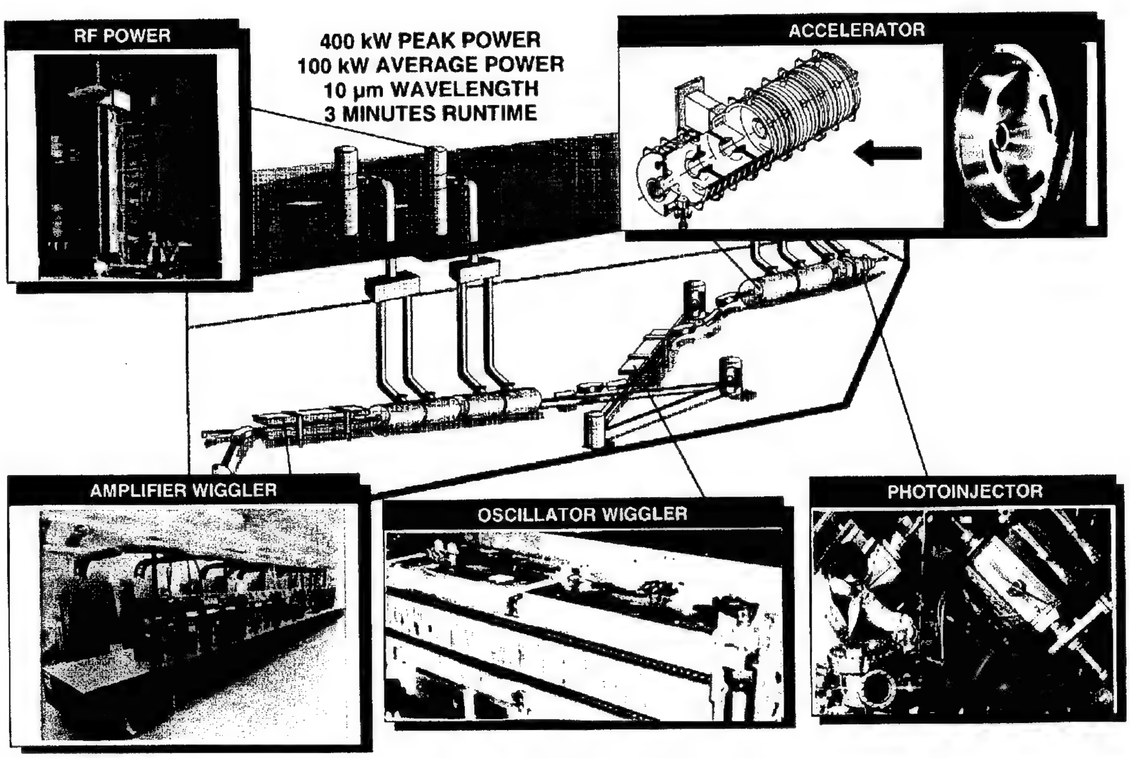

Figure 12 Average Laser Experiment Layout

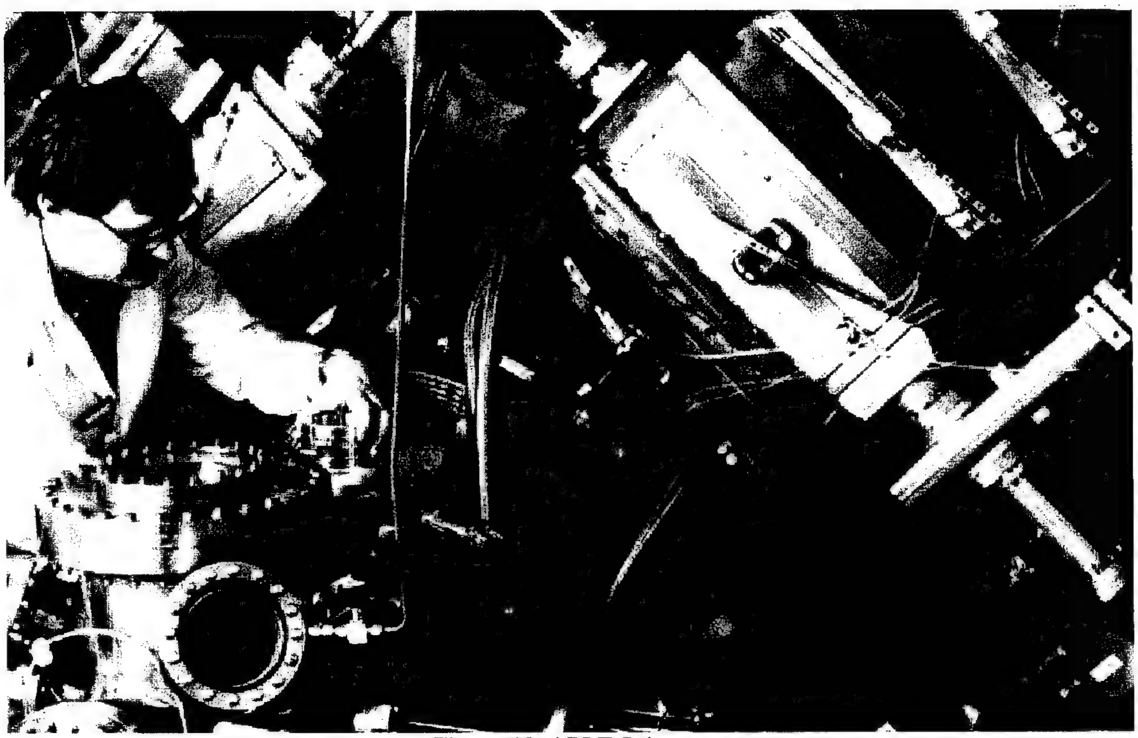

Figure 13. APLE Injector

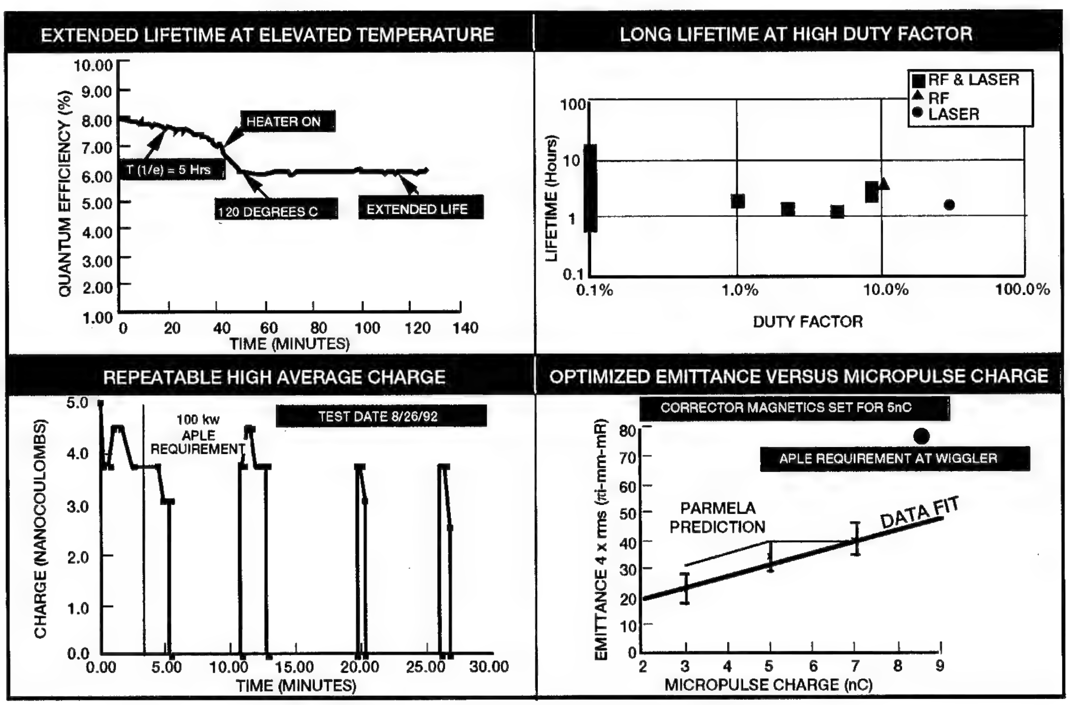

Figure 14. Photocathode Performance

6.2.2 APLE Photoinjector Issues

There were several issues in using the photo cathode for the injector in the baseline APLE design. These were quantum efficiency, photocathode lifetime at high duty factor and high charge, and emittance. All of these issues have been resolved by experimental verification and all APLE baseline requirements have been exceeded. These key issues and demonstrated performance characterisitics of the APLE photo-injector are described below.

a. Quantum Efficiency

The quantum efficiency (Q.E.) requirement for APLE was to produce greater than 2.6% Q.E. for at least 30 minutes. At the end of the development effort, photocathodes were routinely made that exceeded 6% Q.E. for hours. Also, it was shown that heating up the photocathode to 120 C can essentially extend the lifetime indefinitely after initial Q.E. degradation in the first 30 minutes. This is shown in Figure 14a.

b. Photocathode lifetime at high duty factor and high charge.

Prior to the APLE photoinjector development, no photocathodes had ever been run at duty factors exceeding a few percent. Tests with the Boeing/LANL photoinjector at duty factors exceeding 25% demonstrated that the photo-cathode lifetime was independent of duty factor. This is shown in Figure 14b. At 3.5 nC, the 1/e photocathode lifetime had a maximum of 3.2 hours with an average of about 2 hours.

The primary factor effecting photocathode lifetime was determined to be the water partial pressure. Lifetimes exceeding 100 hours were achieved at a 10^{-11} Torr water partial pressure. At water partial pressures of 5×10^{-11} torr, 1/e lifetimes greater than 10 hours were observed. At about 1×10^{-10} torr, the lifetimes were reduced to approximately 1 hour.

The photocathodes must also have a repeatable high average charge at high duty factors. Shown in Figure 14c is a 30 minute run at 4 nC and 18% duty factor where the electron beam is purposely turned on and off to simulate a weapons firing. A continuous run of greater than 5 minutes was demonstrated. The APLE requirement was 3 minutes.

c. Photo-injector emittance.

Emittance measurements were made using two phosphor screens inserted just down stream of the injector cavities. Because of the uncertainty in the displacements caused by the steering coil located after the photocathode, the current in this coil was adjusted over a wide range of values and the emittance measured. Measurements were taken at 1,3,5, and 7 nC (see Figure 14d). The APLE emittance requirement is 75 mm-mr at 8.5 nC. Optimizing the emittance by adjusting the coil current yields about 40 mm-mr at 7 nC. Plotting the trend of optimized emittance versus micropulse charge, an emittance of 45 mm-mr is predicted at 8.5 nC, which is very encouraging [8]. The experimental data also agrees well with PARMELA predictions as shown in Figure 14d.

6.3 APLE Amplifier

The first 5 meters of the Near-Infrared Scalable Undulation System (NISUS) was built by the fall of 1988 and the remaining 5 meters was completed in the spring of 1990 (see Figure 15). The wiggler parameters were tested, (magnetic field strength, gap, uniformity, and period) and the wiggler development was declared a success.

The NISUS wiggler has 256 periods built in 16 modules of 16 periods each. This would allow easy scaling to longer lengths without redesign. It employs samarium cobalt magnets with vanadium permendur poles which produce an on-axis magnetic field strength of 5.6 KGauss with a 3.89 cm period and 1.44 cm gap. The magnetic field may be tapered by varying the gap separation. The taper prescription is remotely adjustable by stepper motor-driven gap mechanisms located at the joints between sections. The NISUS wiggler should produce 10% extraction efficiency at 10 microns for the APLE experiment.

This wiggler marks the culmination of many years of wiggler analysis and development and is the most advanced wiggler of its type in the world today. It is presently being loaned to Brookhaven National Laboratory for use in their FEL program.

6.4 Baseline APLE Performance with Errors

The APLE system was extensively analyzed with INEX. Using the APLE accelerator, wiggler and optical design specifications, and assuming no errors, the optical output power predicted by INEX was 230 kW. Clearly no device is error-free so tolerances were assigned to the acceleration and wiggler [7]. Tolerances were varied to produce several different error sets. The average of the sets was 198 kW (9.9% extraction efficiency) with a worst case (all parameters at maximum) of 184 kW (9.2%

extraction efficiency). When optical tolerances were added to the study, the worst case was 164 kW (8.2% extraction efficiency), still well above the baseline APLE requirement of 100 kW. These results are summarized in Figure 16.

8. Major U.S. FEL'S

The major U.S. FEL facilities are shown on the map in Figure 17 and are briefly described in this section.

Boeing - Used 18 MeV RF Linac/Oscillator configuration for 10 micron light. Then 110 MeV RF Linac/Ring Resonator for 0.6 micron. Phase I of the average power laser experiment (APLE) is to be 10 microns, 18 MeV, 10 kW oscillator. Phase II is to be 10 micron, 34 MeV, 100 kW oscillator and amplifier.

Stanford - (1). The 43 MeV superconducting Accelerator/Oscillator produces 4 micron light. (2). The 5 MeV RF Linac/Oscillator configuration for 85 micron light.

UC Santa Barbara - UCSB interest is in FELS above 10 micron. They have produce 63 and 338 micron light with their 6 MeV electrostatic accelerator/oscillator.

Los Alamos - (1). APEX - 46 MeV RF Linac/Oscillator produced light at 9-35 microns. (2). AFEL - 16 MeV CyroRFlinac/Oscillator produces 4.5 micron light

Univ. of Central FL - Under construction, operational 1995, 1.7 MeV CW Electrostatic accelerator/oscillator projected light 80-220 microns.

Vanderbilt University. - 43 MeV RF Linac/Oscillator produces 2-10 micron light.

Duke University. - (1). 1 GeV Storage Ring Accelerator/Oscillator projected 0.1 to 0.6 micron light. (2). 43 MeV RF Linac/Oscillator produces 2-10 micron light.

Grumman/Princeton - 14 MeV RF Linac/Oscillator produces 14 micron light.

Brookhaven Natl. Lab - 50 Mev RF Linac/Oscillator produced 0.5 micron light. Upgrade 210 MeV RF Linac/Oscillator projected 0.15 to 0.3 micron light in 1995.

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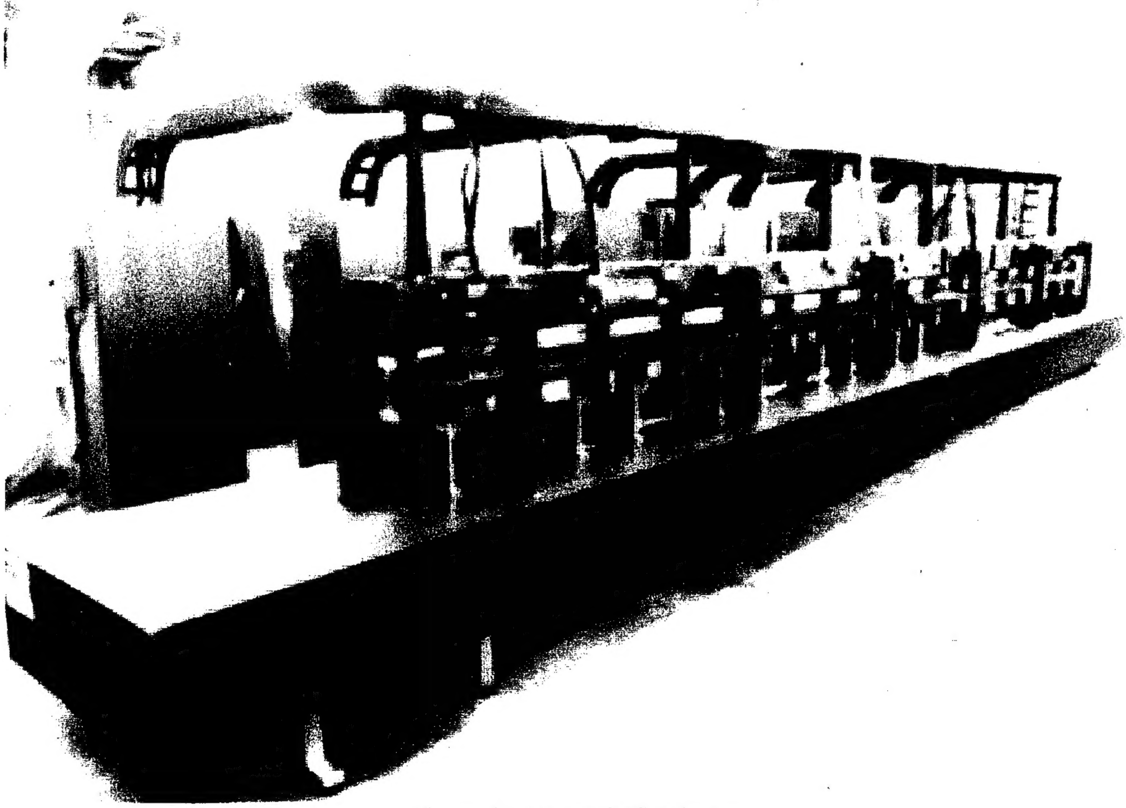
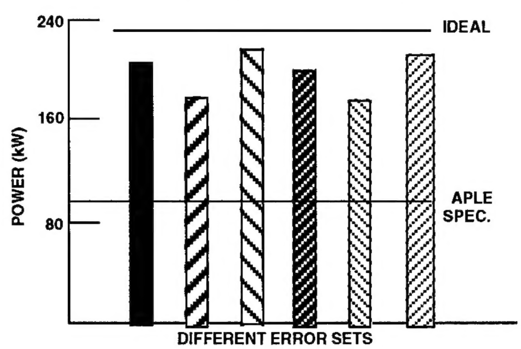


Figure 15. The NISUS Wiggler

TOLERANCES

- ACCELERATOR
  - STEERING ACCURACY = 200 μm RMS
  - MISALIGNMENT = 0.5 μm pk
  - MAGNET CURRENT LEVEL = 1% RMS
  - RF PHASE = 1° RMS
  - RF AMPLITUDE = 1% RMS
- WIGGLER
  - FIELD ERROR = 0.5% RMS
  - BPM ACCURACY = 210 μm RMS
  - GAP ERRORS = 50 μm pk
  - CENTERLINE BOWING = 150 μm pk
  - CORRECTORS = 16
- OPTICAL
  - NO ERRORS

PERFORMANCE



AVERAGE EXTRACTION EFFICIENCY = 9.9%, 198 kW

WORST CASE = 9.2%, 184 kW

PREVIOUS AMPLIFIER SENSITIVITIES INCLUDING OPTICAL ERRORS, WORST CASE > 8.2%, 164 kW

Figure 16. Baseline Performance of APLE with Errors

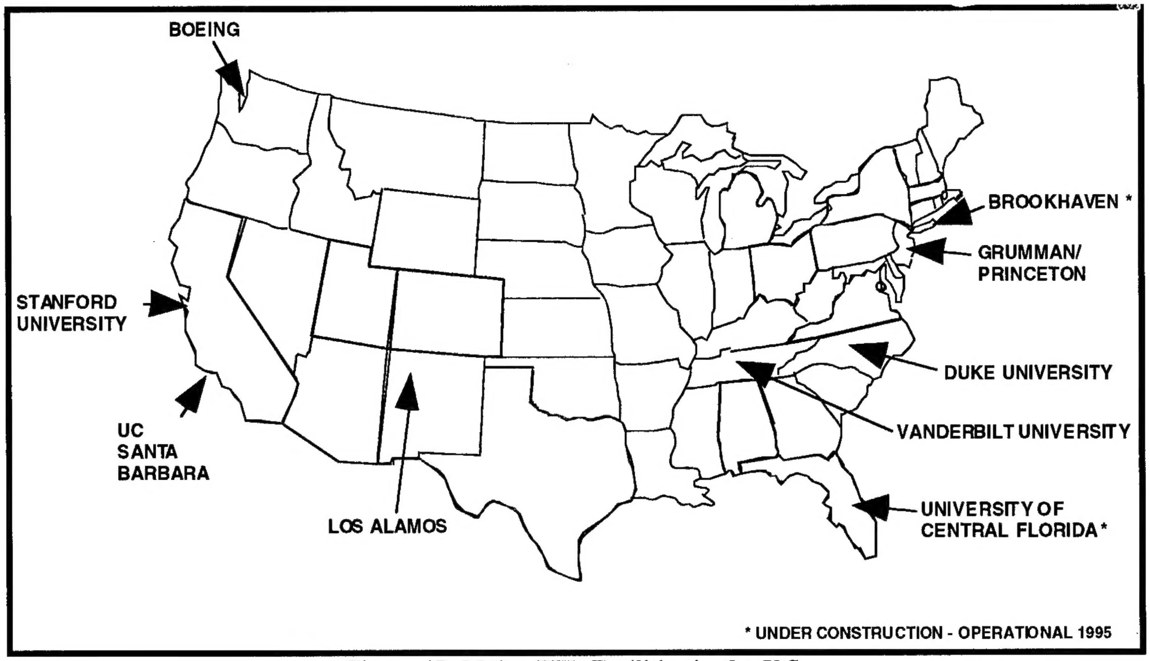


Figure 17. Major FEL Facilities in the U.S.

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This paper provides an overview of the Free Electron Laser weapons development program from its beginnings in 1979 to the present. A historical overview of the programmatics is provided, but the primary emphasis is on the technical accomplishments made during this period.

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